LCA Discussions

Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-indicator 99

Does it matter which one you choose?

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Abstract

Goal, Scope and Background. A number of impact assessment methodologies are available to the LCA practitioner. They differ, and often there is not one obvious choice among them. The question therefore naturally arises: 'Does it make any difference to my conclusions which method I choose?' To investigate this issue, a comparison is performed of three frequently applied life cycle impact assessment methods.

Methods. The three life cycle impact assessment methods EDIP97 [1], CML2001 [2] and Eco-indicator 99 [3] are compared on their performance through application to the same life cycle inventory from a study of a water-based UV-lacquer. EDIP97 and CML2001 are both midpoint approaches and hence quite similar in their scope and structure, and this allows a comparison during both characterisation and normalisation. The third impact assessment method Eco-indicator 99 is an endpoint method and different in scope and structure from the other two. A detailed comparison can not be done but a comparative analysis of the main contributors to the Eco-indicator 99 results and the weighted and aggregated EDIP97 results is performed.

Results and Discussion. Following a translation into common units of the EDIP97 and CML2001 output, differences up to two orders of magnitude are found for some of the indicator results for the impact categories describing toxicity to humans and ecosystems, and there is little similarity in the patterns of major contributors among the two methods. For human toxicity the CML2001 score is dominated by contribution from metals while the EDIP97 score is caused by a solvent and nitrogen oxides. For aquatic ecotoxicity, metals are the main contributors for both methods but while it is vanadium for CML2001, it is strontium for EDIP97. After normalisation, the differences are reduced but still considerable. For the other impact categories, the two methods show only minor differences. The comparison of the main contributors to the Eco-indicator 99 results and the weighted and aggregated EDIP97 results identifies nitrogen oxides as the main contributor for both methods. It is, however, much more dominant for Eco-indicator 99 while the EDIP97 score represents important contributions from a number of different substances, and furthermore, the analysis reveals that the aggregated scores for the two methods come from different impacts. It is thus difficult to extend the findings for these two methods to other inventories.

Conclusion. For EDIP97 and CML2001, it mainly matters which method is used if the chemical impacts on human health and ecosystem health are important for the study. For the other impact categories, the differences are minor for these two methodologies. For EDIP97 and Eco-indicator 99, the patterns of most important contributors to the weighted and aggregated impact scores are rather different, and considering the known differences in the underlying framework and models, the results of the two methods may well go in opposite directions for some inventories even if the conclusion is the same for the inventory studied in this paper.

Recommendations and Outlook. Particularly for the impact categories representing toxic impacts from chemicals, the study demonstrates the need for more a detailed analysis of the causes underlying the big differences revealed between the methods.

Keywords: CML2001 (Life Cycle Assessment – An Operational Guide to the ISO Standards 2001); comparison; criteria; Eco-indicator 99; ecotoxicity; EDIP97 (Environmental Design of Industrial Products); human toxicity; life cycle impact assessment (LCIA); reference substances

Introduction

The framework and principles of life cycle impact assessment have been discussed over the years by consecutive working groups under SETAC resulting in a sequence of consensus-oriented papers describing state of the art [4,5,6]. The area is also addressed in an ISO standard on life cycle impact assessment [7]. Nonetheless, a number of different impact assessment methodologies are available to the LCA practitioner, and several of them are implemented in software commercially available on the market. Often, the LCA practitioner will not find one obvious choice among them, and the question therefore naturally arises: 'Does it make any difference to my conclusions which method I choose?' The present paper reports a comparison of the Danish method *Environmental Design of Industrial Products 1997* (EDIP97) [1] with the two Dutch methods *Eco-indicator 99* [3] and *Life Cycle Assessment – An Operational Guide to the ISO Standards* 2001 (CML2001) [2], all of which have or are anticipated to get, a widespread use in the LCA community.

Comparison procedure. A fundamental difference between the three impact assessment methods is that the CML2001 and EDIP97 methods have a problem-oriented approach to impact assessment as opposed to the Eco-indicator 99 method which has a damage-oriented approach. This means that while the former two model the impacts at a midpoint somewhere in the environmental mechanism between emissions and damages, the latter aims at modelling damage to the protection areas: human health, natural and manmade environment and natural resources. It should be mentioned that an update of EDIP97 is currently being released as EDIP2000 [8] offering site-dependent modelling of the major non-global impact categories, and in several cases moving the indicator point further towards the endpoint. EDIP2000 has not been included in the comparison and will not be discussed further in this paper.

The difference in approach to impact assessment makes it difficult to perform a meaningful comparison between Eco-indicator 99 and the two other methods based on the scores they produce, since they are modelling different aspects and hence give few results which can be compared. The main subject of this study is thus a quantitative comparison of the CML2001 and EDIP97 methods performed on the characterised indicator scores and on the normalised scores, while some more qualitative points regarding the use of midpoint and endpoint methods are illustrated by a comparison of the weighted Eco-indicator 99 and EDIP97 results (**Table 1**).

Table 1: Comparison between the impact assessment methodologies is performed at different levels in the methodology, after characterisation, normalisation or weighting and aggregation

Basis of comparison	CML2001 vs. EDIP97	EI99 vs. EDIP97
Characterised indicator scores	X	
Normalised indicator scores	X	
Aggregated results of weighting		X

A life cycle inventory of a lacquer has been used as basis for the comparison between the methods. The three methods have been applied in strict accordance with the respective methodology guides [3,2,1], and to some extent the methodology background material has been consulted [9,10,11,12]. Only characterisation factors readily available in the respective guides have been applied in the assessments. The scope of the comparison between the three methods concerns impacts on the external environment, i.e. impacts affecting human health and natural and manmade environment.

The object of the comparison – A life cycle inventory of a lacquer. The life cycle inventory data are from a comprehensive study of the environmental exchanges in the life cycle of a water-based UV lacquer produced by Akzo Nobel Industrial Wood Coatings A/S, Denmark. The functional unit of the study is: *decoration and protection of a standard kitchen cabinet door for 20 years*. The goal of the study was to perform a detailed LCA for product documentation. The study is documented in [13]. An excerpt of the most important environmental exchanges from the lacquer product system is presented in **Table 2**.

Table 2: Excerpt of inventory results showing the most important emissions from the lacquer product system

Emissions	Unit	Total
Emissions to Air		
1-methyl-2-pyrrolidone	g	2.04×10^{-7}
Ammonia	g	1.91×10^{-3}
Arsenic	g	5.84×10^{-6}
Butylglycol	g	1.06×10^{-1}
Cadmium	g	6.92×10^{-7}
Carbon dioxide	g	1.46×10^{2}
Carbon monoxide	g	3.33×10^{-1}
CFC-11	g	4.83×10^{-5}
Chlorine	g	4.30×10^{-3}
Chromium	g	2.94×10^{-6}
Copper	g	6.07×10^{-6}
Dichloroethane	g	4.36×10^{-6}
Dioxin	g	5.04×10^{-11}
Dipropylene glycol methylether	g	5.65×10^{-2}
Ethylene glycol	g	5.89×10^{-2}
Fluoride	g	4.21×10^{-7}
Formaldehyde	g	4.33×10^{-9}
Hydrocarbons	g	5.90×10^{-2}
Hydrochloric acid	g	2.57×10^{-7}
Hydrofluoric acid	g	5.18×10^{-7}
Hydrogen sulphide	g	3.03×10^{-5}
Iron	g	4.70×10^{-6}
Lead	g	6.15×10^{-6}
Manganese	g	9.40×10^{-6}
Mercury	g	1.26×10^{-6}
Methane	g	4.04×10^{-1}
Methanol	g	9.36×10^{-8}
N-butoxypropanol	g	7.10×10^{-1}
Nickel	g	1.41×10^{-5}
Nitrogen oxides	g	2.74×10^{0}
Nitrous oxide	g	3.29×10^{-3}
NMVOC	g	6.99×10^{-10}
PAH	g	2.36×10^{-10}
Selenium	g	2.32×10^{-6}
Sulphur dioxide	g	5.04×10^{-1}
Unspecified aldehyde	g	4.50×10^{-7}
Unspecified n-alkane	g	1.63×10^{-6}
Unspecified organic compounds	g	2.70×10^{-3}
Vanadium	g	4.07×10^{-5}
VOC	g	8.56×10^{-3}
Zinc	g	2.98×10^{-5}
Emissions to Soil		
None	–	–
Emissions to Water		
Cadmium	g	6.68×10^{-13}
Chlorine	g	5.23×10^{-5}
Chromium	g	4.13×10^{-5}
Copper	g	5.01×10^{-8}
Fluoride	g	3.97×10^{-5}
Formaldehyde	g	4.68×10^{-8}
Hydrogen ions (H^+)	g	7.98×10^{-4}
Lead	g	3.14×10^{-8}
Manganese	g	1.32×10^{-5}
Mercury	g	6.07×10^{-8}
NH_4^+-N	g	1.82×10^{-3}
Nickel	g	2.48×10^{-6}
Nitrogen oxides	g	3.90×10^{-2}
NO_3^--N	g	1.70×10^{-5}
Phenol	g	1.69×10^{-5}
Phosphate	g	3.86×10^{-3}
Strontium	g	6.62×10^{-5}
Total Nitrogen	g	1.89×10^{-2}
Total Phosphorus	g	2.18×10^{-4}
Zinc	g	2.92×10^{-6}

1 Comparison between EDIP97 and CML2001 Impact Assessment Methods

The comparison between the EDIP97 and CML2001 methods is performed at two stages in the impact assessment, after characterisation and after normalisation.

The obligatory categories of the two methods are similar except for two. Land use recommended by CML2001, but not by EDIP97, is considered irrelevant for the applied case study and is therefore not included here. EDIP97 includes a waste category divided into four types of solid waste for land-filling, for which the disposal is not fully modelled within the product system. In CML2001 no such categories exist and they are therefore also not included in the comparison.

1.1 Normalised results

The normalised results obtained by both the EDIP97 and the CML2001 methods are presented in **Fig. 1**. The normalised impact scores are expressed as milliperson-equivalents, i.e. thousandths of the annual impact from an average person. A first observation from the figure is that the normalised environmental impacts are larger for the CML2001 method than for the EDIP97 method for all impact categories except human toxicity. The relative magnitudes vary and the difference is most pronounced for photochemical ozone formation/summer smog, acidification and aquatic and terrestrial ecotoxicity.

To investigate the reasons for this difference, we first look at the characterised results impact category by impact category.

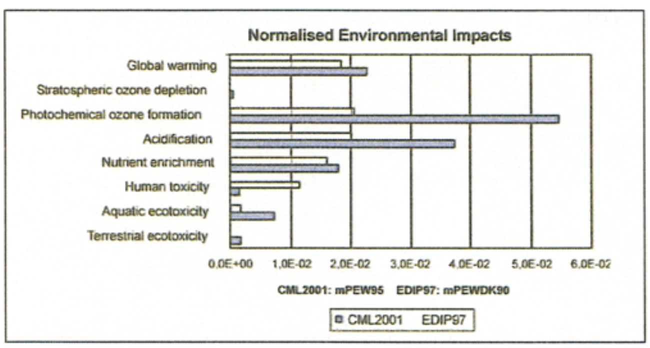

Fig. 1: Normalised impact scores for the lacquer product system applying the CML2001 and EDIP97 impact assessment methods

1.2 Directly comparable impact categories

For the impact categories global warming, stratospheric ozone depletion, acidification and photochemical ozone formation, the characterisation results are expressed in the same or very similar units, and a direct comparison at the category indicator point is thus straight forward (**Table 3**).

With minor modifications, the two methods use the same characterisation models for the categories global warming, stratospheric ozone depletion and nutrient enrichment.

Global warming (Climate change). In EDIP97, the global warming characterisation model is extended compared to CML2001 through inclusion of indirect contributions from methane, non-methane volatile organic compounds (NMVOCs) and carbon monoxide. As can be seen from Table 3, the EDIP97 method consequently calculates a slightly higher global warming impact score than the CML2001 method. The difference is primarily caused by a higher characterisation factor for methane while the indirect contributions from the NMVOCs are insignificant.

Table 3: Characterised indicator results for the lacquer product system applying EDIP97 and CML2001 methodology

Impact category	Unit	EDIP97	CML2001
Climate change	g CO_2-eq	160	155
Stratospheric ozone depletion	g CFC 11-eq	$4.8{\times}10^{-5}$	$4.8{\times}10^{-5}$
Photochemical ozone formation	g C_2H_4-eq	0.41	0.44
Acidification	g SO_2-eq	2.48	1.98
Nutrient enrichment	g PO_4^{3-}-eq	0.38	0.41
Human toxicity	g $C_6H_4Cl_2$-eq	61.6	13.2
Aquatic ecotoxicity	g $C_6H_4Cl_2$-eq	0.78	640
Terrestrial ecotoxicity	g $C_6H_4Cl_2$-eq	$6.1{\times}10^{-3}$	$8.4{\times}10^{-2}$

Stratospheric ozone depletion. The stratospheric ozone depletion potential is the same when the two methods are applied to the water-based lacquer inventory, which only contains one contributing substance, namely the reference substance for this impact category, CFC11. The difference may be more pronounced for product systems involving more ozone-depleting substances, since the factors recommended in CML2001 are more recent than the factors of EDIP97.

Nutrient enrichment (Eutrophication). The nutrient enrichment impact is expressed in equivalents of different reference substances (nitrate in EDIP97 and phosphate in CML2001) even though the same characterisation model is used by the two methods. A major difference between the two methods is that the contribution of COD is included in the CML2001 method despite the fact that COD does not contribute to nutrient enrichment or eutrophication at the indicator point which defines the category (but to some of the consequences later in the environmental mechanism like oxygen depletion). When the EDIP97 results are translated to phosphate equivalents, a direct comparison is possible showing a slightly higher impact score for the CML2001 method due to the inclusion of a contribution from COD (see Table 3).

Acidification. For acidification, the characterisation model applied in the CML2001 method includes a larger part of the environmental mechanism than the model used by EDIP97. The CML2001 model, however, only includes emissions of nitrogen oxide, sulphur dioxide and ammonia to air. The higher acidification score in Table 3 obtained for the EDIP97 method is caused by the contribution from acidifying emissions to water, especially hydrogen ions.

Photochemical ozone formation (Photo-oxidant formation). The characterisation models used by the two methods for photochemical ozone formation are quite similar – both are based on the Harwell Laboratories' Trajectory model – and

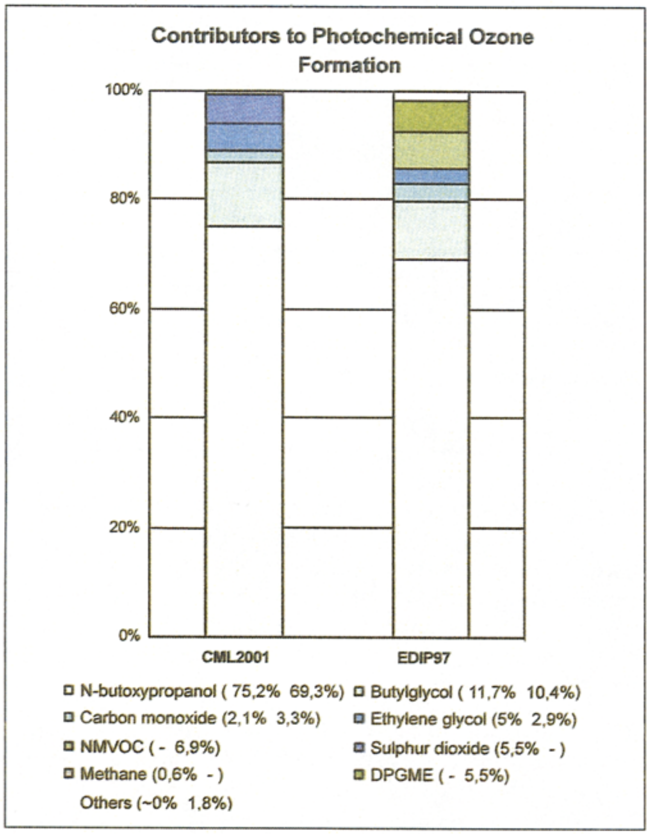

Fig. 2: Main contributors to photochemical ozone formation from the lacquer product system applying the CML2001 and EDIP97 impact assessment methods. (DPGME stands for Dipropylene Glycol Methyl Ether)

from **Fig. 2** it is clear that most of the major contributors pointed out by both methods are the same. EDIP97, however, also includes characterisation factors for different groups of NMVOCs, while CML2001 includes summer smog with SO_2 as main contributor. In addition, the characterisation factors for unsaturated organic compounds are generally found to be higher in CML2001 than in EDIP97. This means that although the relative scores of the individual organic compounds are similar as seen from Fig. 2, there is a minor difference in the absolute scores for all the organic solvents emitted in the life cycle of the lacquer and altogether this leads to the difference in the total scores for this impact category seen in Table 3.

1.3 Human toxicity and ecotoxicity

For the human toxicity and ecotoxicity categories, the characterised results of the CML2001 and EDIP97 impact assessments are not directly comparable because the CML2001 results for these categories are expressed in 1,4-dichlorobenzene (1,4-DCB) equivalents while the EDIP97 results are expressed as a volume of the end compartments of the substance. Furthermore, the two methods consider partially different subcategories and aggregate them in a different manner.

The CML2001 method expresses the human toxicity impact in one total score while EDIP97 gives a human toxicity score for each end compartment (air, water, soil). Therefore, a modification is introduced to facilitate the comparison of the toxicity results. According to the EDIP97 method, an aggregation of the subcategory results should occur after normalisation but for the sake of analysis of the characterised results, the indicator results for human toxicity via air, soil and water are aggregated into one score after translation of the EDIP97 characterisation score into units of a common reference substance similar to what is done in CML2001. To facilitate the comparison, the reference substance of the CML2001 method, 1,4-DCB is applied. The conversion of the EDIP97 characterisation factors (CF) follows **Equation 1**.

$$\frac{CF_A\ [m^3\ \text{compartment} / g\ A]}{CF_{1.4-DCB}\ [m^3\ \text{compartment} / g\ 1.4-DCB]} = CF_A\ [g\ 1.4-DCB / g\ A] \qquad (1)$$

For the subcategories of ecotoxicity there are also differences between the characterised output of the two methods. The EDIP97 method distinguishes between acute and chronic ecotoxicity in water, i.e. between short-term and long-term toxic effects, while the CML2001 method only considers chronic effects in the ecotoxicity category. The acute ecotoxicity considered by the EDIP97 method can therefore not be included in the comparison. The CML2001 method on the other hand distinguishes between ecotoxicity in fresh water and marine water. EDIP97 does not have this distinction and since the major impacts are expected to occur in marine waters, the EDIP97 method's chronic ecotoxicity in water is compared to the CML2001 marine subcategory. The fresh water category of the CML2001 method is excluded from the comparison. The excluded scores constitute less than one percent of the overall ecotoxicity scores determined by EDIP97 and CML2001 respectively, which means that the exclusion has little influence on the comparison. In addition to the aquatic subcategories, both methods include a terrestrial ecotoxicity subcategory.

The ecotoxicity subcategories are compared separately here, because aggregation is not recommended as a standard procedure in CML2001 as it is for the human toxicity categories. For the sake of comparison between the two methods, the EDIP97 ecotoxicity characterisation factors are converted into 1,4-DCB equivalents in the same way as for human toxicity – see equation 1.

The impact scores determined by the two methods show substantial differences, as well in magnitude as in main contributors for both the human toxicity and the ecotoxicity categories. This is shown in Table 3 and in Figs. 3 and 4.

Human toxicity. Table 3 shows that the characterised human toxicity impact score calculated with the EDIP97 method is nearly five times larger than the score calculated with the CML2001 method. The causes behind this dramatic difference are likely to be found in the different characterisation models applied by the two methods. The characterisation modelling performed in the two methods consists of the same elements – fate and exposure analysis and effect analysis. Particularly for the fate and exposure modelling, there are, however, fundamental differences. While EDIP97 applies a simplified approach based on environmental key

properties like (bio)degradability, volatility and lipophilicity, CML2001 applies an integrated environmental multimedia model, USES-LCA[1]. The individual steps in the CML2001 method's fate and exposure modelling are not immediately transparent to the user due to the application of USES-LCA, and this impedes a detailed comparison between the two methods' characterisation modelling. It is thus only possible to point out where differences in the characterisation modelling are expected, but it is not straightforward to assess how these differences are reflected in the magnitude of the characterisation factors and consequently in the impact score due to the limited background available in the CML scientific background [11].

The effect analysis is quite similar, since both methods apply an acceptable daily dose or inhalation concentration as effect indicator. Different choice of toxicity test results or assessment factors in calculation of the dose may, however, also account for some differences between the resulting characterisation factors. This has not been investigated.

In part, the explanation of the larger human toxicity score obtained by EDIP97 could also be that the EDIP97 method provides characterisation factors for a larger number of the substances occurring in the inventory than the CML2001 method.

It is clear from **Fig. 3** that the human toxicity potential is caused by different substances in the two methods. According to the CML2001 method, the human toxicity score in the life cycle of the water-based lacquer is primarily caused by emissions of chromium, arsenic and nickel (from the generation of electricity). According to the EDIP97 method, the main contributors to the human toxicity score are ethylene glycol (from the lacquer) and nitrogen oxides (from generation of electricity and other incineration) while the contributions from the metals are insignificant.

The CML2001 method does not provide a characterisation factor for ethylene glycol, which turns out to be of major significance for the human toxicity score obtained with the EDIP97 method, and the factor for nitrogen dioxide is rather low[2]. The EDIP97 method, on the other hand, does not include ammonia, which is an important contributor to the CML2001 human toxicity score. Overall, the CML2001 method assesses the toxicity impact of the metals to be higher than the EDIP97 method. It is, however, interesting that lead and mercury, the only metals of importance in the results from the EDIP97 method, are insignificant in the CML2001 results due to the dominance of chromium. The toxicity of lead and mercury thus contributes with less than 0,06% to the total CML2001 score.

It is difficult to say if the results would be more alike if the methods had included characterisation factors for the same substances. As a general observation, the CML2001 method puts a strong weight on the human toxicity of metals, and the CML2001 characterisation factors are smaller for non-

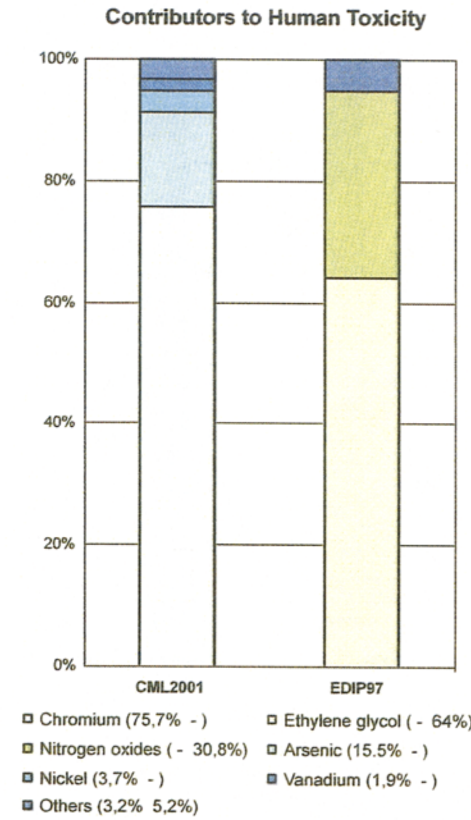

Fig. 3: Main contributors to human toxicity from the lacquer product system applying the CML2001 and EDIP97 impact assessment methods

metals than for metals except for extreme toxins like dioxin and PAH. Therefore, it is not obvious that the inclusion of nitrogen oxide and ethylene glycol would have made the results of the two assessments more alike. It is not exactly specified in the CML2001 guide [2] or in the scientific background [11] how the USES model is modified to include metals; therefore, it is difficult to elaborate on this result without a more in-depth research of the CML method. The CML2001 guideline, however, does mention that the use of infinite time horizon makes the metals more influential since they possess the ultimate persistence in the environment.

Overall, it may be seen as surprising that the main human toxicological impacts from a lacquer should be caused by metals emitted from the electricity generation rather than organic solvents emitted during the application of the lacquer (even though the lacquer is water-based and hence contains moderate quantities of organic solvents).

Ecotoxicity. As can be seen from Table 3, the ecotoxicity scores are much higher using the CML2001 method than the EDIP97 method. This is the opposite of what was found for human toxicity. For aquatic ecotoxicity, the CML2001 score is roughly 800 times higher and for terrestrial ecotoxicity 14 times higher.

Terrestrial ecotoxicity contributes less than 1 percent to the overall ecotoxicity score for both methods. Therefore, the focus in the comparison is on the aquatic ecotoxicity. As for

[1] USES-LCA is a version of USES 2.0 that has been developed for use in risk assessment of non-polar organic chemicals within the EU. USES-LCA has been modified to represent the conditions valid for LCA and to include other substance groups like metals relevant for LCA purposes.

[2] CML does not include nitrogen oxides (NOx), but only nitrogen dioxide.

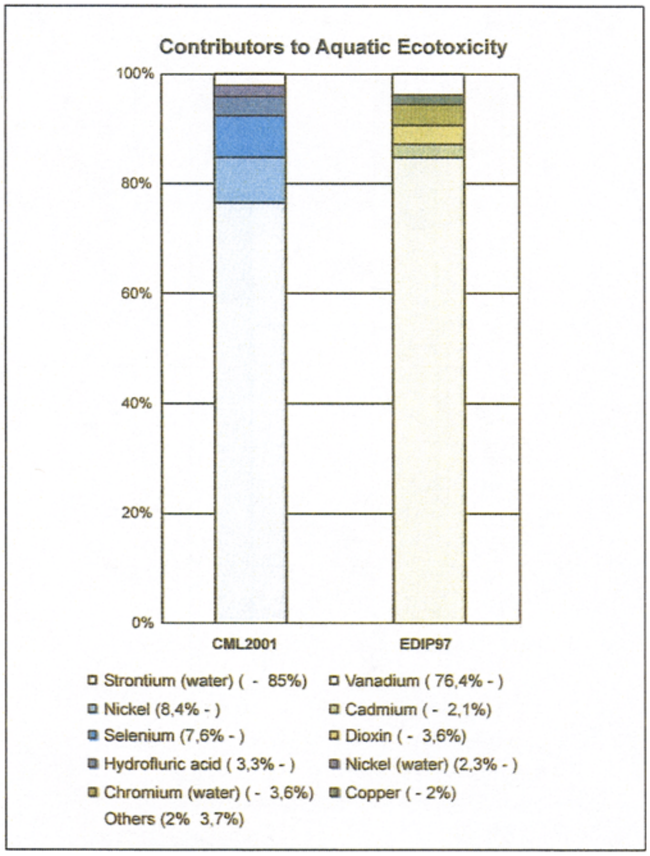

Fig. 4: Main contributors to aquatic ecotoxicity from the lacquer product system applying the CML2001 and EDIP97 impact assessment methods

human toxicity, the causes behind the large difference are likely to be found in the characterisation modelling. The characterisation modelling performed in the two methods consists of the same elements as for human toxicity and the considerations about these are also valid for ecotoxicity modelling.

Fig. 4 reveals that hardly any of the main contributors to aquatic ecotoxicity are the same for the two methods. The CML2001 ecotoxicity score is primarily caused by contributions from vanadium, nickel and selenium (emitted to air) whereas the ecotoxicity score according to the EDIP97 method primarily consists of contributions from strontium (emitted to water), dioxin and chromium (emitted to water). Nickel is the only major contributor for both methods, albeit not with the same importance. The dominating metals, vanadium for the CML2001 method and strontium for the EDIP97 method, are both emissions from electricity generation. A noteworthy observation is that the dominating substances for the CML2001 result are metals, which are also included by EDIP, but not pointed out as being important.

There is a difference in the inventory coverage of the two methods. Apart from the metals shown by name in Fig. 4, CML2001 includes factors for the aquatic ecotoxicity of ethylene and PAH while EDIP97 includes methanol, n-butanol, ethylene glycol, and manganese but none of these have significant contributions to the aquatic ecotoxicity impact. The CML2001 and EDIP97 method both put little weight on the aquatic ecotoxicity of non-metals, except for dioxin, which EDIP 97 designates as important. It is observed that the characterisation factors applied by CML2001 generally are much higher for all metals than the EDIP97 factors (after translation of these into 1,4-DCB equivalents). An extreme example is the characterisation factor for aquatic ecotoxicity of nickel emitted to air, which is a million times higher according to CML2001 than to EDIP97.

1.4 Implications in the use of a reference substance for the human and ecotoxicity categories

As mentioned above, a noteworthy difference between EDIP97 and CML2001 is that the CML2001 method expresses the characterisation factors for both human toxicity and ecotoxicity relative to a common reference substance. This is a normal procedure in LCIA for most of the other impact categories which are more homogenous in the sense that all contributing substances act according to the same or very similar environmental mechanisms. For homogenous impact categories, the reference substance will follow the same mechanism as the other substances assigned to the impact category. Human toxicity and ecotoxicity, in contrast to most of the other impact categories, are very inhomogeneous covering many different environmental mechanisms. Therefore, the use of a reference substance may be problematic, and it has not been implemented in EDIP97 [9].

The use of reference substance can be seen as a kind of internal normalisation within the impact category where the impacts from all other substances in a given compartment are expressed relative to the impact from the reference substance in the same compartment. The characteristics of the reference substance are thus quite important, not only in determining the size of the characterisation factors, but also in determining the relative magnitude of the modelled impacts in the different compartments. If the reference substance has a very low impact in water and a high impact in soil, the characterisation factors for all other substances will be biased accordingly, and the modelled impact in the water compartment will be shown as higher compared to the modelled impact in the soil when expressed relative to the reference substance. This bias will vary with the choice of reference substance, and be most pronounced for substances with a toxicity pattern which differs from that of the reference substance. In the case of human toxicity, the distortion thus introduced is drawn into the substance's characterisation factor when impacts for different compartments are aggregated into one factor. For ecotoxicity, where CML2001 keeps the scores for the compartments separately, the bias introduced by the choice of reference substance will be counteracted when a normalisation is performed.

In the comparison between EDIP97 and CML2001, the conversion of the EDIP97 scores into 1,4-DCB equivalents may also introduce a bias between the characterised toxicity scores. For EDIP97 1,4-DCB ranks around the median of all substances for which characterisation factors have been given (see [1]) for the ecotoxicity subcategories, around the 30 percentile for human toxicity via air and around the 80 percentile for human toxicity via water. For CML2001 1,4-DCB ranks in the low end for aquatic ecotoxicity and hu-

Table 4: Relative rank of 1,4-dichlorobenzene among substances for which characterisation factors are given in [5] and [6]

Impact category	CML2001	EDIP97
Human toxicity, air	Low	Low to middle
Human toxicity, water	Middle	High
Aquatic ecotoxicity	Low	Middle
Terrestrial ecotoxicity	Middle	Middle

man toxicity via air, and in the middle for terrestrial ecotoxicity and human toxicity via water as summarised in **Table 4**. The relatively lower ranking of the reference substance for aquatic ecotoxicity in CML2001 may contribute to the large impact score when compared to the EDIP97 score (See Table 3). The difference in ranking between CML2001 and EDIP97 for human toxicity via air may introduce a bias in the aggregated characterisation factors for human toxicity but this can not be substantiated from the available data. Overall, the conversion of the EDIP97 scores into 1,4-DCB may have some influence on the outcome of the comparison between the two methods.

1.5 The importance of normalisation references

For both methods the normalisation references are chosen to represent the impacts, which society imposes on the environment in one year. The impacts elicit effects on different spatial scales. Some impacts are global of nature, others are more regional. For the sake of the weighting which may follow normalisation, it is chosen in EDIP97 to let the normalisation references reflect this difference in scale and hence, the global impact per year is used as normalisation reference for global impact categories while the regional impact (typically the region is Denmark or Europe) is used for regional impact categories. All normalisation references are expressed as person equivalents, i.e. in relation to the number of people contributing with emissions at the chosen scale. The CML2001 method does not recommend this distinction between spatial scales but advocates the use of normalisation references for one spatial scale only. The CML2001 method includes local, regional and global normalisation references, but the global normalisation references are recommended as default. The CML2001 global normalisation references are based on world data for emissions in the reference year 1995 while EDIP97 uses 1990 as reference year. In addition to this difference, the quality of the emission data applied by EDIP97 and CML2001 to calculate normalisation references may vary, but it has not been possible to decide this from the methodology backgrounds.

Non-(eco)toxicity impacts. As seen from Table 3, differences in the characterised impact scores are quite insignificant for the categories global warming, stratospheric ozone depletion, acidification, nutrient enrichment, and photochemical ozone formation. From Fig. 1 it is evident that the normalisation increases the difference for these category indicator scores. In all cases, the CML2001 scores increase relative to the EDIP97 scores upon normalisation. The effect is most pronounced for the photochemical ozone formation impact score and for the acidification and global warming scores where the dominance (albeit weak) of the EDIP97 score after characterisation is reverted. These changes arise because the CML2001 normalisation references are lower than the EDIP97 references. The difference is probably caused in part by the more recent reference year applied in CML2001 (in the cases where the background impact has been going down since 1990) and, for the regional impact categories by the fact that the global person equivalent applied by CML2001 is lower than the European or Danish person equivalent applied by EDIP97.

Human and ecotoxicity impacts. Upon normalisation, the difference in human toxicity scores obtained by the two methods increases a little whereas the difference between the ecotoxicity scores is dramatically reduced. For human toxicity and ecotoxicity impacts, it is not possible to compare the normalisation references directly as applied by the two methods. As mentioned earlier, the CML2001 method expresses the impacts and hence also the normalisation references relative to 1,4-DCB, and this conversion has not been possible to perform to the EDIP97 normalisation reference (see [9]). It is, however, obvious from the results that while the human toxicity normalisation references must be rather equivalent, the CML2001 normalisation reference for aquatic ecotoxicity must be several orders of magnitude higher than the EDIP97 reference.

1.6 Does it matter whether you choose CML2001 or EDIP97?

The environmental profiles of the water-based lacquer shown in Fig. 1 do not, at a first glance, seem all that different. The two profiles agree on the order of relevance of the four most important impacts. The photochemical ozone formation and acidification impacts are more pronounced in the CML2001 profile, but the analysis reported in this paper has shown that this is primarily due to differences in the normalisation step and not the characterisation modelling. Differences arising in the normalisation may be seen as less problematic because they are well defined and independent of the concrete study. They will thus be the same when the methods are applied to another inventory. More problematic are the differences in the aquatic ecotoxicity impact determined by EDIP97 and CML2001. The normalised scores are almost the same, but this is rather a coincidence since the main contributors are quite different and the characterised results differ by orders of magnitude. For aquatic and terrestrial ecotoxicity, and for human toxicity, the differences in the scores obtained by the two methods may reflect the significant differences particularly in the fate-modelling applied in the methods for human and ecotoxicity. This becomes even more obvious when the main contributors are identified.

For the toxicity impacts, the differences found when using EDIP97 and CML2001 will be strongly dependent on the substances appearing in the inventory and therefore on the type of product. A different inventory might result in a different pattern, and for the impact categories concerning human and ecotoxicity, it may thus make a big difference which of the two methods is chosen for the life cycle impact assessment. For the other impact categories, the differences are minor, and if assessment of the toxicity impacts is not

crucial to the goal of the LCA, or if the contributions to these two categories are insignificant for the product in question, it makes little difference, which of the two impact assessment methods is applied.

2 Comparison of EDIP97 and Eco-indicator 99 Impact Assessment Methods

EDIP97 and Eco-indicator 99 are very different impact assessment methods. While EDIP97 is a midpoint approach as presented above, Eco-indicator 99 is a damage or an endpoint approach proceeding from the identification of areas of concern (damage categories) to determination of what causes damage to these. The top down approach, where modelling is performed from endpoint towards point of exchanges, impedes a free selection of impact categories as these are linked to the choice of damage categories determined from the start, and this difference prevents a direct comparison of the individual elements of the assessment as done for EDIP97 and CML2001 above.

The Eco-indicator 99 method considers three damage categories: human health, ecosystem quality and resources. **Table 5** shows the three damage categories and the concomitant impact categories modelled in Eco-indicator 99.

Table 5: The damage categories and the underlying impact categories modelled in Eco-Indicator 99

Damage categories	Impact categories
Human Health	Carcinogenic effects on humans
	Respiratory effects caused by organic substances
	Respiratory effects caused by inorganic substances
	Damage caused by climate change
	Effects caused by ionising radiation
	Effects caused by ozone layer depletion
Ecosystem Quality	Damage caused by ecotoxic effects
	Damage caused by the combined effect of acidification and eutrophication
	Damage caused by land occupation and land conversion
Resources	Damages caused by extraction of minerals
	Damages caused by extraction of fossil fuels

As mentioned earlier, the impact on resources is not included in this method comparison, and damage to resources is therefore not considered in the ecoindicator focusing it exclusively on the environmental impact pathways. For the comparison of EDIP97 and Eco-indicator 99, the default version of the latter[3] is applied.

Impact assessment according to Eco-indicator 99 is performed in two steps, where step one is the actual damage modelling and step two consists of normalisation and weighting. The damage modelling for human health and ecosystem quality is based on fate-, exposure-, effect- and damage analysis. The outcome of the Eco-indicator 99 damage modelling for environmental impacts is a human health damage score expressed as Disability Adjusted Life Years (DALY) and an ecosystem quality damage score expressed as Potentially Disappeared Fraction (PDF). In the normalisation step, the relative contribution of the calculated damages to the total damage caused by a reference system is determined, similar to what is done by EDIP97 for environmental impacts. The Eco-indicator 99 normalisation references are based on European data on air emissions whereas data on emissions to water and soil are extrapolated from data from the Netherlands.

While the normalisation component has much in common for EDIP97 and Eco-indicator 99, the two methods use different weighting methods. The Eco-indicator 99 method uses a panel approach, while the EDIP97 method uses a distance to target method applying political reduction targets. The goal of both weighting methods is to reflect the society's view on, which damages or potential impacts are of greatest importance. The result of the EDIP97 method is a profile of weighted impact scores expressed as Person Equivalents Targeted for the year 2000 (PET_{2000}), whereas the result obtained with the Eco-indicator 99 method is expressed as a single ecoindicator score expressed as ecopoints, where one ecopoint can be interpreted as one thousandth of the annual environmental load of one average European inhabitant.

For the sake of comparison, the weighted EDIP97 results are also aggregated into one score by taking the average score of the impact categories. The result of the aggregation represents the functional unit's share of the targeted annual impact from an average person. The aggregated EDIP97 score is $1{,}4 * 10^{-2}$ $mPET_{2000}$ while the ecoindicator is $1{,}16 * 10^{-2}$ ecopoints. The two aggregated scores have a similar meaning, and it is therefore interesting to observe that they also have similar values.

Subsequently, a contribution analysis is performed for both, tracing the most important contributors. **Fig. 5** shows the result of the contribution analysis.

Both the Eco-indicator 99 and EDIP97 method have nitrogen oxides, mainly from incineration of the lacquer in the disposal stage, as the most important contributor to the overall weighted impact but with different relative significance. Nitrogen oxides contribute approximately one third to the total score for EDIP97, and the double for Eco-indicator 99. A noteworthy difference between the two results is that the EDIP97 score has as number of other significant contributors, including three solvents (totalling 27%), while the Eco-indicator 99 score is dominated by the contribution from Nitrogen oxides (65%) and unspecified particles (16%). Eco-indicator 99 does include the three solvents pointed out by the EDIP97 method, but these are only minor contributors. Presumably, the damage modelling is based on their indirect impact through formation of photo oxidants and the inclusion of direct human exposure to the solvents might increase their relative contribution to the overall score. The EDIP97 method, on the other hand, does not model the environ-

[3] The hierarchist perspective with average weighting set is recommended as default in the Eco-indicator Methodology report [2].

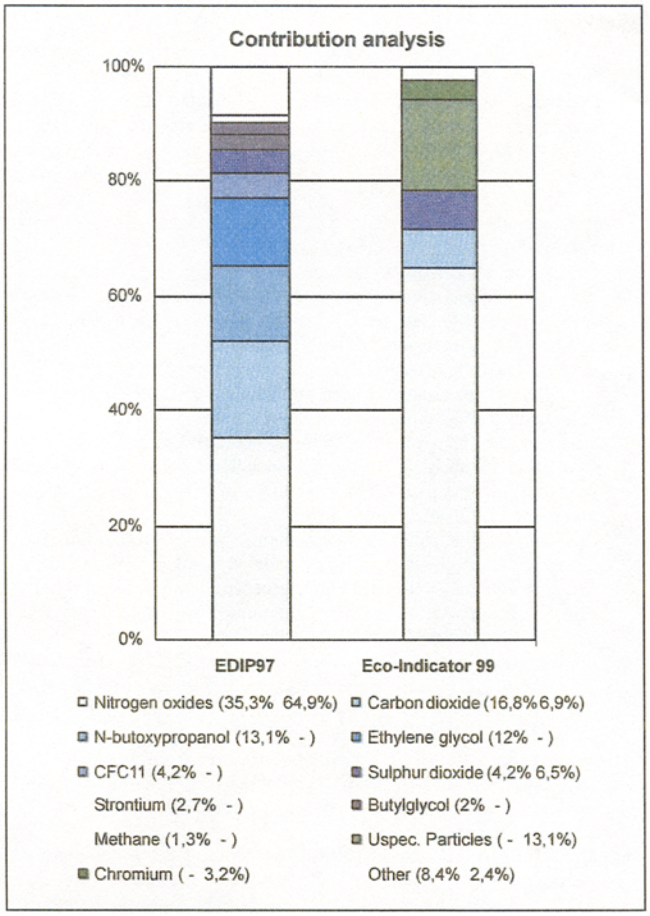

Fig. 5: Main contributors to the damage or impact score for the lacquer product system after weighting applying the Eco-indicator 99 and EDIP97 impact assessment methods

mental impact from emission of particles, but only considers it in relation to working environment, which is not included in this comparison of methods.

The damage category Human Health is the main contributing category to the damage result obtained by Eco-indicator 99 with an 89% contribution. The primary contributing impact category to Human Health is *Respiratory effects from inorganic substances*, which constitutes three quarters of the ecoindicator value. The emissions contributing to this subcategory thereby have a major impact on the result reached with the Eco-indicator 99 method – in this case nitrogen oxides (54%) and unspecified particles (16%). No single impact category has such a large effect on the result found with the EDIP97 method, where several impact categories have the same order of magnitude in the environmental profile of the lacquer.

The damage category Ecosystem Quality contributes with the remaining 11% of the ecoindicator. This contribution all stems from the subcategory *Acidification and nutrient enrichment* which again is totally dominated by the contribution from nitrogen oxides.

The strong weight put on the emission of nitrogen oxides by the Eco-indicator 99 method seems to be caused by the fact that the method has a very small normalisation reference for the Human Health damage category compared to the references for the two other damage categories combined with the fact that the damage factor for nitrogen oxides is large compared to majority of the substances included by the method. The weighting factors for the damage categories Human Health and Ecosystem Quality are of the same magnitude and do therefore not contribute to the difference.

The nitrogen oxides emission also influence the result reached with the EDIP method. Here the contribution primarily stems from the acidification and nutrient enrichment impacts and secondarily from the human toxicity impact.

2.1 Does it matter whether you choose Eco-indicator 99 or EDIP97?

The two methods give aggregated results of the same order of magnitude but apart from the focus on the emission of nitrogen oxides, there is little concordance between the results of the two methods. The Eco-indicator 99 method points out two major contributors, whereas the result reached with the EDIP97 method has a large number of different contributors. Due to the fundamental differences in the underlying modelling, described above, and in substance coverage, it is foreseeable that the two methods may produce diverging results, were they to be applied to comparisons of other types of products.

3 Conclusion

It has been shown that in some cases it does matter which impact assessment method is chosen.

While a superficial observation indicates very similar impact patterns for the CML2001 and EDIP97 methods in Fig. 1, a deeper analysis has revealed that only for the mainly energy-related impact categories global warming (climate change), photochemical ozone (photo-oxidant) formation, nutrient enrichment (eutrophication) and acidification, and for stratospheric ozone depletion, the results are really comparable.

For the toxicity related impact categories, the indicator results as well as the patterns of main contributors are quite different. The effect modelling applied in the two methods is very similar and the main cause is assumed to be the fundamental differences in the fate and exposure modelling. CML2001 is based on an adaptation of an integrated multimedia model (USES) developed for risk assessment of chemicals while EDIP97 applies a rather simple modular fate model developed from an identification of the environmental key properties of substances. An additional source of difference may be the fact that CML2001 uses a reference substance for aggregation of human toxicity exposure along different routes. On top of this, normalisation references are also different but in the case investigated here, these differences tend to have a neutralising effect.

CML2001 does not support weighting and aggregation into one score results. It has therefore not been possible to compare this method to Eco-indicator 99 but a comparison of aggregated EDIP97 scores and Eco-indicator 99 scores shows agreement on the overall magnitude of the aggregated score and on the most important contributor. The pattern of other

important contributors is, however, rather different, and considering the known differences in the underlying framework and models, it is concluded that the results of the two methods may well go in opposite directions for other products than the lacquer analysed here.

3.1 When the different impact assessment methods may give different results, which one should you then choose?

The second SETAC-Europe working group on life cycle impact assessment has developed a number of criteria for evaluation of characterisation methods. Some central criteria are [14]:

- Scientific validity – are the underlying methods generally accepted in the international scientific community?
- Environmental relevance of the indicator scores – is it possible to interpret them in terms of environmental impact or damage?
- Reproducibility and transparency –is there a well-defined and transparent procedure for calculating characterisation factors and indicator scores?
- Quantification of uncertainty of the indicator scores?
- Feasibility – is it feasible to find or to calculate characterisation factors for all the most important substances in the inventory?

To these criteria might be added: Does the result of the use of the method seem reasonable and is it in accordance with experience from use of other environmental assessment tools?

For some applications, not all methods are eligible and this may determine the choice. For use in decision contexts like product development where alternatives are compared regularly by actors with low environmental expertise, it may thus be a requirement that the method can provide aggregated one score results.

4 Recommendations and Outlook

Environmental impacts from chemicals is a concern in the life cycle of many products, and therefore it is important for the credibility of Life Cycle Assessment that chemical impacts be included in a fair and representative way in the impact assessment. One of the obstacles to such an inclusion is the lack of consensus on the methodology for the assessment of ecotoxicity and human toxicity which is reflected in the existence of a number of available models. This paper has revealed fundamental differences particularly for these impact categories and pointed to the need for a more thorough comparative analysis of the existing methods. Such a comparison is underway in a joint EU programme involving the two universities behind the CML and EDIP methods together with a number of other European universities and industry partners (the OMNIITOX project – Operational Models aNd Information tools for Industrial applications of eco/TOXicological impact assessments [15]).

Also for the other impact categories there are important differences, particularly when comparing a midpoint methodology like EDIP97 and an endpoint methodology like Eco-indicator 99. This points to the importance of the joint UNEP/SETAC Life Cycle Initiative which aims at identification of and consensus creation on recommendable practices within life cycle assessment and life cycle management [16]. The Life Cycle Initiative has a sub programme on life cycle impact assessment which some years from now may help reduce uncertainties on which life cycle impact assessment method to choose.

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